

# Lepton Flavor Violation in Linear Colliders

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In this talk, we review how Linear colliders will enable us to study flavor physics.

N. Arkani-Hamed *et. al.*, Phys. Rev. Lett. **77**, 1937 (1996) [arXiv:hep-ph/9603431]. D. Nomura, Phys. Rev. D **64**, 075001 (2001) [arXiv:hep-ph/0004256]; J. Hisano, *et. al.*, Phys. Rev. D **60**, 055008 (1999) [arXiv:hep-ph/9808410]; M. Guchait, *et. al.*, Eur. Phys. J. C **21**, 163 (2001) [arXiv:hep-ph/0103161]; F. Deppisch *et. al.*, arXiv:hep-ph/0310053; N. Arkani-Hamed *et. al.*, Nucl. Phys. B **505**, 3 (1997) [arXiv:hep-ph/9704205]; M. Dine *et. al.*, eConf **C010630**, P332 (2001) [Int. J. Mod. Phys. A **18**, 2757 (2003)] [arXiv:hep-ph/0111154]

Generally, mass terms are

$$-\tilde{L}_{Li}^\dagger (m_{\tilde{L}}^2)_{ij} \tilde{L}_{Lj} - \tilde{l}_{Ri}^\dagger (m_{\tilde{R}}^2)_{ij} \tilde{l}_{Rj} \\ -(m_{\tilde{R}\tilde{l}}^2)_{ij} \tilde{l}_{Ri} \tilde{l}_{Lj}$$

Notice that  $\tilde{L}_{Lj} = (\tilde{\nu}, \tilde{l}_{Lj})$ .

The off-diagonal terms are lepton flavor violating and can result in flavor violating rare decays.

Particle Data Group Booklet

$$\text{Br}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11} \quad \text{Br}(\tau \rightarrow e\gamma) < 2.7 \times 10^{-6}$$

and

K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0310029.

$$\text{Br}(\tau \rightarrow \mu\gamma) < 3.1 \times 10^{-7}$$

For  $m_{susy} \simeq 200$  GeV,

$$\frac{(m_{\tilde{L}(\tilde{R})}^2)_{e\mu}}{m_{susy}^2} < \text{few} \times 10^{-4} \quad \frac{(m_{\tilde{R}\tilde{l}}^2)_{e\mu}}{m_{susy}^2} < \text{few} \times 10^{-6}$$

$$\frac{(m_{\tilde{L}(\tilde{R})}^2)_{\tau e}}{m_{susy}^2} < 0.1 \quad \frac{(m_{\tilde{R}\tilde{l}}^2)_{\tau e}}{m_{susy}^2} < \text{few} \times 10^{-2}$$

$$\frac{(m_{\tilde{L}(\tilde{R})}^2)_{\tau\mu}}{m_{susy}^2} < \text{few} \times 10^{-2} \quad \frac{(m_{\tilde{R}\tilde{l}}^2)_{\tau\mu}}{m_{susy}^2} < 10^{-2}$$

I. Masina and C. A. Savoy, Nucl. Phys. B **661**, 365 (2003) [arXiv:hep-ph/0211283].

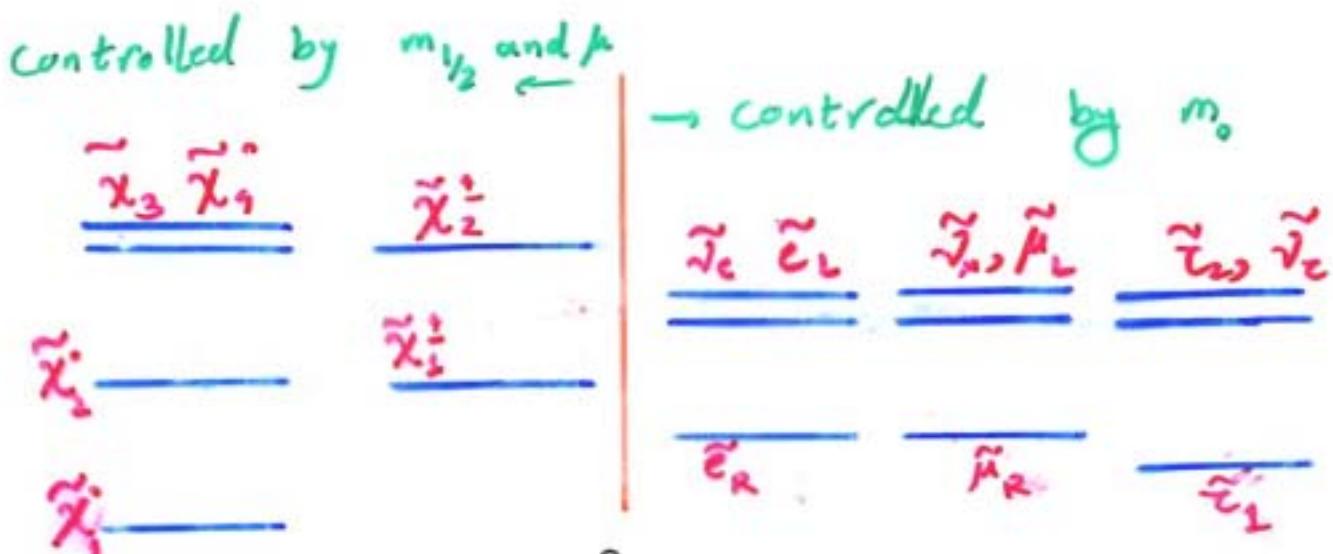
## mSUGRA

At the GUT scale,

$$m_{\tilde{L}}^2 = m_{\tilde{R}}^2 = m_0^2 \text{ and } A_{ij}^{(l)} = a_0 Y_{ij}^{(l)}$$

and the masses of gauginos are given by the single parameter  $m_{1/2}$ .

At the electroweak scale,



We will assume  $\tilde{\chi}_1^0$  (the lightest neutralino) is the LSP (as it is convenient for the dark matter).

Depending on  $m_{1/2}/m_0$ ,  $\tilde{L}_L$  can be heavier/lighter than  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$ .

In the MSSM, neutrinos are massless.

Neutrino observations → Neutrinos are massive.

The MSSM cannot be the whole story.

**Seesaw Mechanism:** tiny but nonzero mass for neutrinos

$N_1, N_2$  and  $N_3$  with  $M_1, M_2, M_3 \gg m_{susy}$

$$W = Y_l^{ij} H_d l^c R_i L_j - Y_\nu^{ij} H_u N_i L_j + \mu H_u H_d$$

$$+ \frac{1}{2} M_{ij} N_i N_j,$$

$$Y_l^{ij} = \text{diag}(Y_e, Y_\mu, Y_\tau) \quad M^{ij} = \text{diag}(M_1, M_2, M_3).$$

At the GUT scale

$$\begin{aligned} V_{soft} &= m_0^2 \tilde{N}_i^\dagger \tilde{N}_i + (B M_{ij} \tilde{N}_i \tilde{N}_j / 2 + h.c.) \\ &\quad - A_\nu^{ij} \tilde{N}_i H_u \tilde{L}_j, \end{aligned}$$

where  $A_\nu^{ij} = a_0 Y_\nu^{ij}$

Flavor violating neutrino Yukawa couplings radiatively induce lepton violating masses for the left-handed sleptons ( $\tilde{L}$ ); i.e., that is for  $\alpha \neq \beta$  at the electroweak scale,

$$(m_{\tilde{L}}^2)_{\alpha\beta} = - \sum_k \frac{Y_\nu^{k\alpha} (Y_\nu^{k\beta})^*}{16\pi^2}$$

$$[3m_0^2(\log \frac{\Lambda_{GUT}^2}{M_k^2} - 1) + a_0^2(\log \frac{\Lambda_{GUT}^2}{M_k^2})].$$

F. Borzumati and A. Masiero, *Phys. Rev. Lett.* **57** (1986) 961

Also large  $B$  induce

$$(m_{\tilde{L}}^2)_{\alpha\beta} = \dots - 2 \sum_k \frac{Y_\nu^{k\alpha} (Y_\nu^{k\beta})^* \text{Re}[a_0 B^*]}{(4\pi)^2}$$

and

$$-iA_l^{ji} = -ia_0 Y_l^{ji} \delta_{ij} - \frac{i}{(4\pi)^2} Y_l^{jj} (Y_\nu^{kj})^* Y_\nu^{ki} B$$

Y. F., hep-ph/0310055

Also, large  $B$  can result in **sneutrino-antisneutrino** oscillation. However for the scenario we are considering ( $\tilde{\chi}_1^0$  is the LSP and sneutrino can decay to  $\tilde{\chi}_1^0$ ), no **sneutrino-antisneutrino** oscillation effect will be observable in the linear Colliders.

Y. Grossman and H. E. Haber Phys. Rev. Lett. **78** (1997) 3438.

For this talk, we assume that the dominant source of LFV is  $m_{\tilde{L}}^2$ :

Diagonal  $m_{\tilde{R}}^2$

Diagonal  $m_{\tilde{R}\tilde{l}}^2$

**Non – Diagonal**  $m_{\tilde{L}}^2$

Therefore  $\tilde{l}_L$  and  $\tilde{\nu}$  oscillate while  $\tilde{l}_R$  does not.

## Slepton Oscillation

In the presence of off-diagonal masses (**mixing**),

$$|(\tilde{l}_L)_\alpha\rangle = \sum_i W_{\alpha i} |(\tilde{l}_L)_i\rangle$$

also

$$|(\tilde{\nu}_L)_\alpha\rangle = \sum_i W'_{\alpha i} |(\tilde{\nu}_L)_i\rangle$$

As time passes,

$$|(\tilde{l}_L)_\alpha\rangle = \sum_i e^{im_i t} e^{-\Gamma t} W_{\alpha i} |(\tilde{l}_L)_i\rangle \quad \text{also}$$

also

$$|(\tilde{\nu}_L)_\alpha\rangle = \sum_i e^{im_i t} e^{-\Gamma t} W'_{\alpha i} |(\tilde{\nu}_L)_i\rangle$$

Note that  $\Gamma \sim 1$  GeV and therefore time-dependence cannot be resolved. All the observable quantities are time-integrated.

There are two comments in order:

- 1) To observe slepton oscillation in a collider an intermediate state  $\tilde{\nu}_L$  or  $(\tilde{l}_L)$  has to be produced on-shell.
- 2) Slepton oscillation is given by  $\frac{\Delta m}{\Gamma}$  while LFV rare decays are given by  $\frac{\Delta m}{m_0}$ .  $\Gamma \sim 10^{-3} m_0$ .

This suggests that it may be possible to have observable LFV effect in linear colliders despite the strong upper limit on  $\Delta m$  from the rare lepton number violating decays.

N. Arkani-Hamed, J. L. Feng, L. J. Hall and H. C. Cheng,  
Nucl. Phys. B **505**, 3 (1997) [arXiv:hep-ph/9704205];  
M. Dine, Y. Grossman and S. Thomas, eConf **C010630**,  
P332 (2001) [Int. J. Mod. Phys. A **18**, 2757 (2003)]  
[arXiv:hep-ph/0111154].

## Phenomenological implication of left-handed slepton oscillation in linear colliders

D. Nomura, Phys. Rev. D **64**, 075001 (2001) [arXiv:hep-ph/0004256]; J. Hisano et. al., Phys. Rev. D **60**, 055008 (1999) [arXiv:hep-ph/9808410]; M. Guchait et. al., Eur. Phys. J. C **21**, 163 (2001) [arXiv:hep-ph/0103161]; F. Deppisch et. al., arXiv:hep-ph/0310053.

Implicit assumption: the beams are energetic enough to produce two left-handed sleptons.

To study:  $e^+e^- \rightarrow \tilde{l}_R\tilde{l}_L$

For  $2m_{\tilde{l}_L} > \sqrt{s}$ , this will be the only possibility for LFV.

$$e^+ e^- \rightarrow e\tau + X$$

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First

$$e^+ e^- \rightarrow \tilde{l}_L \tilde{l}_L^c \rightarrow e\tau \tilde{\chi}_1^0 \tilde{\chi}_1^0 \equiv e\tau + \text{missing energy}$$

SUSY-Background:

$$e^+ e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow e\tau \nu \nu \tilde{\chi}_1^0 \tilde{\chi}_1^0 \equiv e\tau + \text{missing energy}$$

SM-Background:

$$e^+ e^- \rightarrow W^+ W^- \rightarrow e\tau \nu \nu \equiv e\tau + \text{missing energy}$$

or

$$e^+ e^- \rightarrow W^+ W^- Z \rightarrow e\tau \nu \nu \nu \nu$$

some clever cuts

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F. Deppisch, H. Pas, A. Redelbach, R. Ruckl and Y. Shimizu,  
arXiv:hep-ph/0310053; D. Nomura, Phys. Rev. D 64,  
075001 (2001) [arXiv:hep-ph/0004256]

If  $\tilde{\chi}_2^0$  and  $\tilde{\chi}_1^+$  are lighter than  $\tilde{L}_L$  new modes are possible.

$$e^+ e^- \rightarrow \tilde{\nu} \tilde{\nu}^c \rightarrow e \tau \tilde{\chi}_1^+ \tilde{\chi}_1^\pm$$

Then  $\tilde{\chi}_1^\mp \rightarrow 2\text{jets} + \tilde{\chi}_1^0$ . Result:

$$e^+ e^- \rightarrow e \tau + 4\text{jets} + \text{missing energy}$$

Or

$$e^+ e^- \rightarrow \tilde{l}_L \tilde{l}_L^c \rightarrow e \tau \tilde{\chi}_2^0 \tilde{\chi}_2^0$$

Then

$$\tilde{\chi}_2^0 \rightarrow 2\text{jets} + \tilde{\chi}_1^0 \quad \text{or} \quad \tilde{\chi}_2^0 \rightarrow l^+ l^- \tilde{\chi}_1^0$$

Final result:

$$e^+ e^- \rightarrow e \tau + 4\text{jets} + \text{missing energy}$$

$$e^+ e^- \rightarrow e \tau + l^+ + l^- + \text{missing energy}$$

## Backgrounds

SM Background:

$$e^- e^+ \rightarrow W^+ W^- Z \rightarrow \tau\tau + 4\text{jets}$$

Then  $\tau \rightarrow \mu(e)\nu\bar{\nu}$ .

SUSY background:

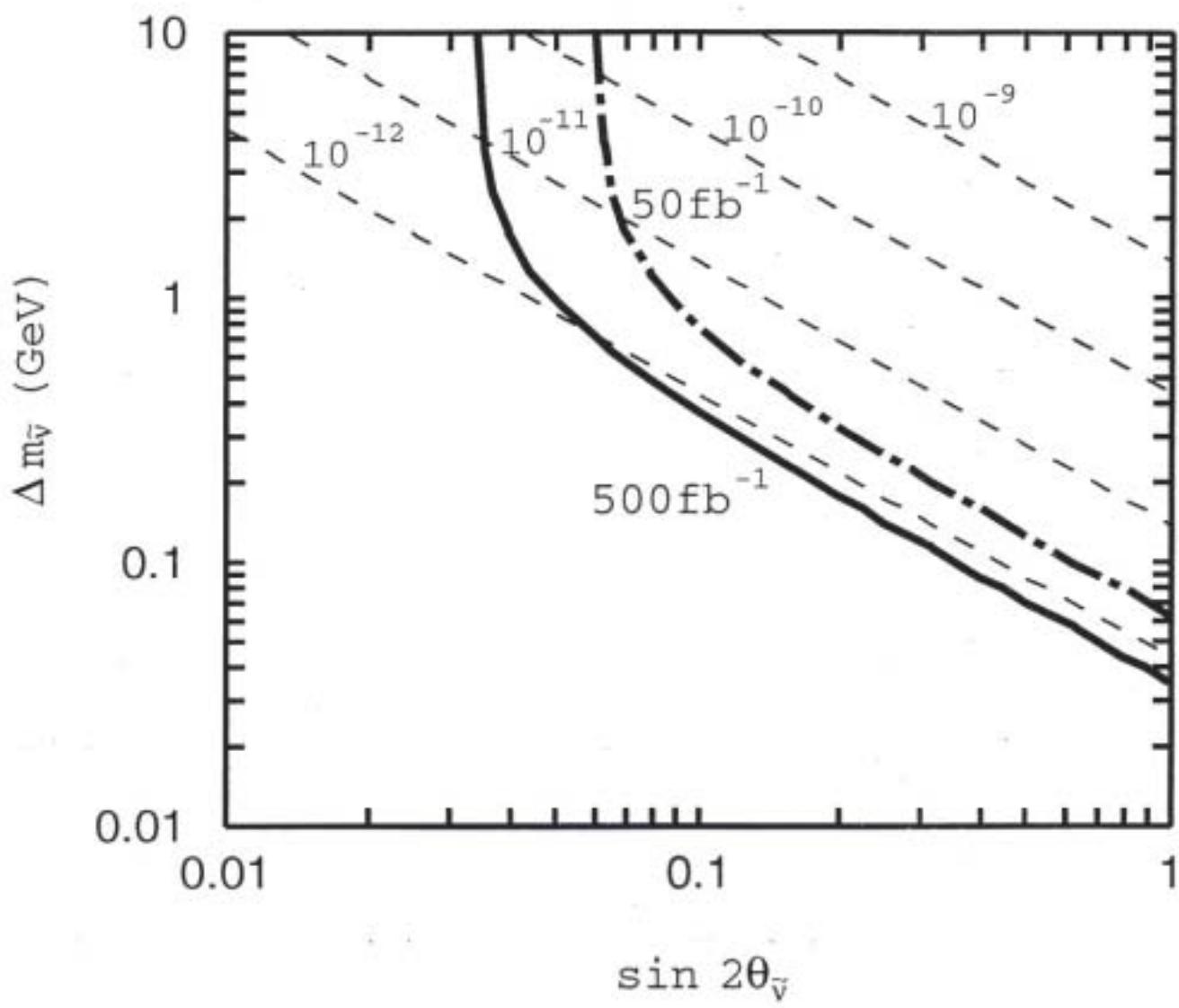
$e^- e^+ \rightarrow \tilde{\tau}\tilde{\tau}$  or  $\tilde{\nu}_\tau\tilde{\nu}_\tau \rightarrow \tau\tau + 4\text{jets} + \text{missing energy}$

Again,  $\tau \rightarrow \mu(e)\nu$ .

D. Nomura, Phys. Rev. D **64**, 075001 (2001) [arXiv:hep-ph/0004256]; J. Hisano *et. al.*, Phys. Rev. D **60**, 055008 (1999) [arXiv:hep-ph/9808410]

By employing cuts on impact parameter and  $E_\mu$  it is possible to reduce the probability of misidentification of  $\tau$  down to 0.02.

$\tilde{\nu}_\tau - \tilde{\nu}_e$  mixing



D. Nomura, Phys. Rev. D **64**, 075001 (2001)  
[arXiv:hep-ph/0004256]

For  $\mathcal{L} = 50 \text{ fb}^{-1}$  ( $500 \text{ fb}^{-1}$ ) and  $\sqrt{s}=500 \text{ GeV}$   
at  $5\sigma$  C.L.

$$\sin 2\theta > 0.06(0.04) \quad \Delta m_{\tilde{\nu}} > 0.07(0.04) \text{ GeV}$$

Much better than near future  $\tau \rightarrow e\gamma$

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$$e^+ e^- \rightarrow \mu\tau + X$$

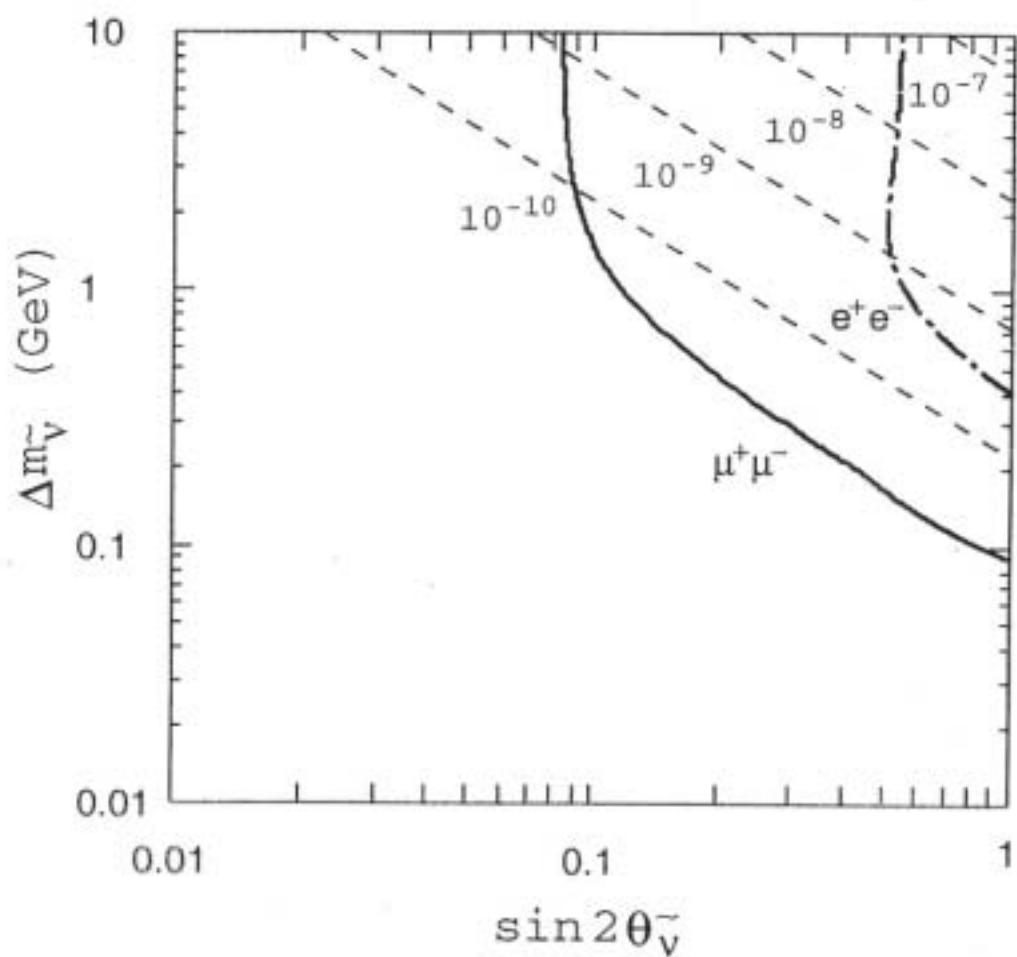
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J. Hisano, M. M. Nojiri, Y. Shimizu and M. Tanaka,  
Phys. Rev. D **60**, 055008 (1999) [arXiv:hep-ph/9808410].

For  $\mathcal{L} = 50 \text{ fb}^{-1}$

$$\sin 2\theta > 0.5 \quad \Delta m_{\tilde{\nu}} > 0.4 \text{ GeV}$$

$$\nu_{\tilde{e}} - \nu_{\tilde{\mu}}$$



$\mu^+\mu^-$  colliders can work better than  $e^-e^+$  colliders.

### Sub-dominant channels

M. Guchait, J. Kalinowski and P. Roy, Eur. Phys. J. C **21**, 163 (2001) [arXiv:hep-ph/0103161].  
 $e^+e^- \rightarrow \tilde{\chi}_2^\pm \tilde{\chi}_1^\mp$

$$\tilde{\chi}_2^\pm \rightarrow \tau^\pm(\mu^\pm)\tilde{\nu}_{2,3} \quad \tilde{\nu}_{2,3} \rightarrow \mu^\mp(\tau^\mp)\tilde{\chi}_1^\pm$$

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_0 + q + q'$$

Although, increasing  $\sqrt{s}$ , new channels will open but statistics will decrease:

For relatively light  $\tilde{L}_L$ ,  $\sqrt{s} = 500$  GeV is better than  $\sqrt{s} = 800$  GeV.

$$e^+ e^- \rightarrow e\mu + X$$

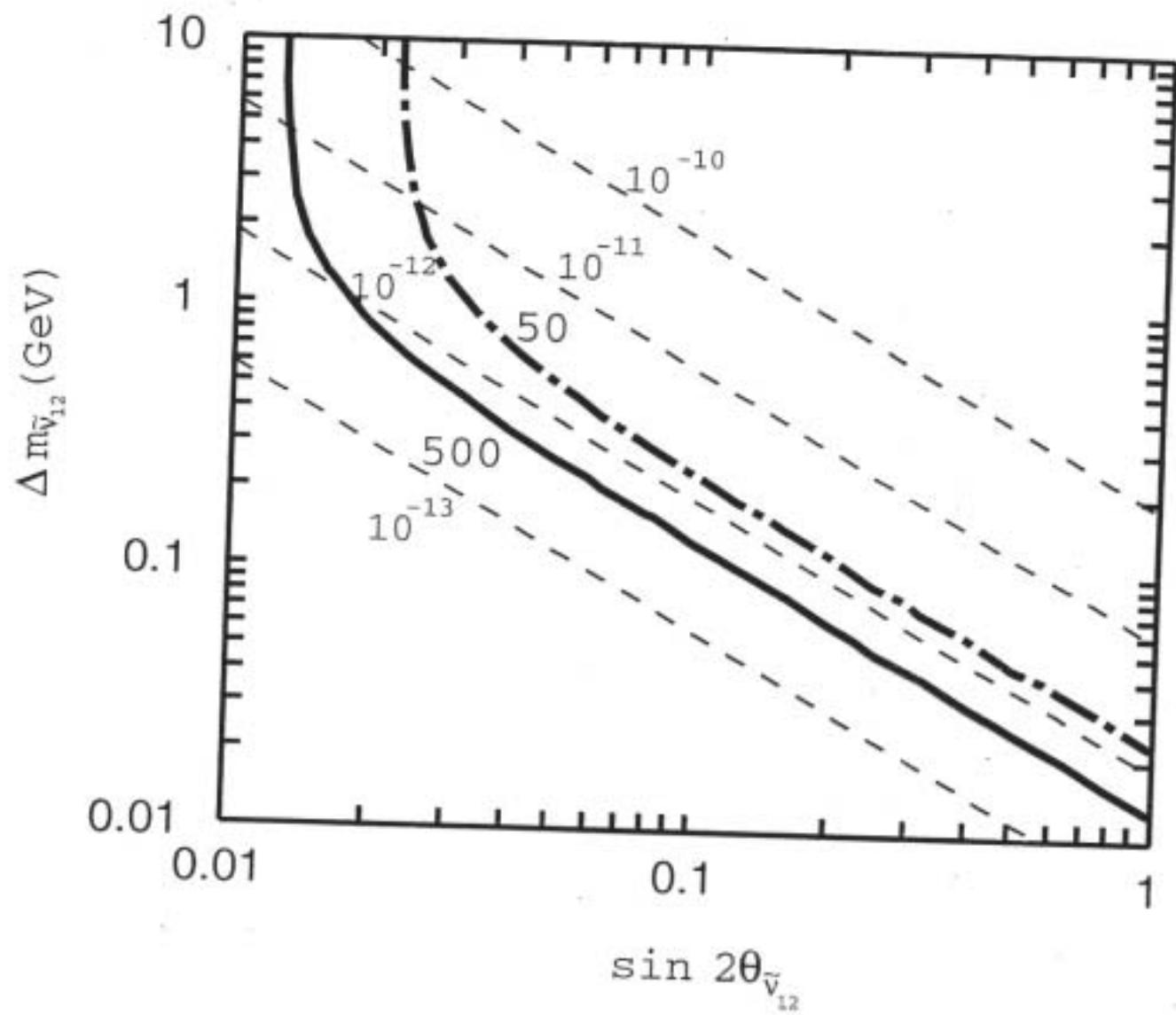
There is already a strong bound on this mode from  $\text{Br}(\mu \rightarrow e\gamma)$ .

The present bound  $\text{Br}(\mu \rightarrow e\gamma) < 10^{-11}$  can be probed by LC however the future bounds from the rare decay will be even stronger:

By 2005, PSI  $\text{Br}(\mu \rightarrow e\gamma) < 10^{-14}$

Beyond the reach of future colliders

$\tilde{\nu}_\mu - \tilde{\nu}_e$  mixing



## CP-violation

$$|(\tilde{l}_L)_\alpha\rangle = \sum_i W_{\alpha i} |(\tilde{l}_L)_i\rangle$$

also

$$|(\tilde{\nu}_L)_\alpha\rangle = \sum_i W'_{\alpha i} |(\tilde{\nu}_L)_i\rangle$$

$W$  is a  $3 \times 3$  matrix

Like CKM and MNS matrices, we can define a [Jarlskog invariant](#).

The CP-violating phase comes from  $Y_\nu$  and can be related to [leptogenesis](#).

CP-violation:

$$\sigma(e^+ e^- \rightarrow \alpha^+ \beta^- X) - \sigma(e^+ e^- \rightarrow \alpha^- \beta^+ X) \neq 0$$

N. Arkani-Hamed, J. L. Feng, L. J. Hall and  
H. C. Cheng, Nucl. Phys. B 505, 3 (1997)  
[arXiv:hep-ph/9704205].

$$\sigma(e^- e^+ \rightarrow \tilde{l}_R \tilde{l}_R^c \rightarrow \alpha\beta + \text{missing energy})$$

By polarizing the initial beam, the background  
can be reduced.

Diagonal  $m_{\tilde{R}}^2$  but non-Diagonal  $m_{\tilde{L}}^2$

To be explored

The basic idea of CP-violation will be the same  
but the details will be different.

General case:

Non-diagonal  $m_{\tilde{L}}^2$ ,  $m_{\tilde{R}}^2$   $m_{\tilde{L}\tilde{R}}^2$

W. Porod and W. Majerotto, Phys. Rev. D **66**, 015003 (2002); W. Porod and W. Majerotto, arXiv:hep-ph/0210326.

Despite severe bounds from rare decays, in general we expect sizable LFV signal in LC even without any cut.

**Question:** Can we figure out what combination of  $m_{\tilde{L}\tilde{R}}^2$   $m_{\tilde{L}}^2$ ,  $m_{\tilde{R}}^2$  is the source of LFV signal?

## Summary

- We expect a large signal of  $e^-e^+ \rightarrow e\tau + 4\text{jets} + \text{missing energy}$ .
- We expect an observable signal of  $e^-e^+ \rightarrow \mu\tau + 4\text{jets} + \text{missing energy}$ .
- The future LFV rare decay searches (PSI) will be more powerful than LC in exploring  $(m_{\tilde{L}}^2)_{e\mu}$ .
- There are still open questions.